NASA TN D-518

7N-05
199037
528

TECHNICAL NOTE
D-518

IMPORTANT RESEARCH PROBLEMS IN ADVANCED FLIGHT STRUCTURES DESIGN - 1960

Edited by
Norris F. Dow
in collaboration with the
NASA Research Advisory Committee on Structural Design

NASA Headquarters
Washington, D. C.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON June 1960

LS

TABLE OF CONTENTS

Page

L
1
2
2
4

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

TECHNICAL NOTE D-518

IMPORTANT RESEARCH PROBLEMS IN ADVANCED FLIGHT STRUCTURES DESIGN - 1960

Edited by
Norris F. Dow
in collaboration with the
NASA Research Advisory Committee on Structural Design

L
1
2
2
4

SUMMARY

Research problems related to advanced flight structures are reviewed to define areas of needed emphasis. These areas include: (1) studies of characteristics of planetary and space environments as they relate to structural design; (2) investigations of methods of control of the environmental hazards; (3) evaluations and developments of advanced structural configurations; (4) improvements in methods of structural analysis; and (5) studies of materials selection and development. Important problems in each of these areas are delineated. Facilities and flight investigations required are described and recommended. Improved integration of structures and materials research is indicated to be a vital factor in the development of advanced flight structures.

The outstanding problem areas are designated and assigned "priorities" to indicate their relative urgency.

INTRODUCTION

The purpose of this report is to review current and future problems in the design of flight structures to define areas in which research should be done. Flight structures as used in this paper are considered to include airborne structures (such as advanced aircraft), missiles, satellites, and space vehicles of all types. The source material comprises previous similar reviews existing in the literature (refs. 1 to 9), and the background of experience of members of the NASA Research Advisory Committee on Structural Design, personnel of the NASA Research Centers, and their colleagues in industry. The relation of structures problems to those delineated in similar surveys in other fields such as materials (refs. 9 to 14) and fatigue (ref. 15) has also been considered in order that the conclusions reached here should be in balance with those in related areas.

In the first part of this report, which is entitled "CONCLUSIONS AND RECOMMENDATIONS," the problem areas are discussed briefly, and the research items which are of greatest urgency are identified. The second part comprises five appendices which explore the problem areas in considerable detail and enumerate specific research studies which are needed to advance the state-of-the-art in structural design. It is recognized that some of the important problem areas are under vigorous attack by the NASA and others, and their inclusion in this report is intended to be a recommendation that this effort be continued. The other important problems need augmentation of effort or the initiation and implementation of research so that solutions may be available for future vehicles.

L1224

Appendix A presents the membership of the NASA Research Advisory Committee on Structural Design who were responsible for the present report. The Editor also wishes to acknowledge the assistance of the following NASA Staff Representatives who worked with the Committee:

Mr. Richard R. Heldenfels, Langley Research Center

Mr. Glen Goodwin, Ames Research Center

Mr. Jack B. Esgar, Lewis Research Center

Mr. J. D. Burke, Jet Propulsion Laboratory

Mr. Melvin G. Rosche, Headquarters

CONCLUSIONS AND RECOMMENDATIONS

As a result of this survey and evaluation of the problems of advanced flight structures, the NASA Research Advisory Committee on Structural Design has arrived at conclusions and recommendations which may be classed under three headings as follows:

I. Important areas for research emphasis

II. Required research facilities and flight tests

III. Integration of research on structures and materials

These conclusions and recommendations derive directly from the more detailed consideration of the various problem areas in the appendices of this report. Additional interpretation is presented under the section entitled "ASSIGNMENT OF PRIORITIES."

I. Important Areas for Research Emphasis

Environment.- The environment encountered is a major factor in determining both the loadings to which the structure is subjected and, in many cases, the response of the structure to these loadings. Continued emphasis must therefore be placed upon the determination of the environmental characteristics of importance to flight structures as indicated below:

Within the Earth's Atmosphere

(1) Improved knowledge of turbulence at both very low and very high altitudes.

(2) Characteristics of transmission of acoustic excitations as from boundary-layer turbulence and from jet and rocket exhausts.

(3) Intensities of energetic particle radiation to determine the significance of this radiation for manned airborne and space vehicles above 50,000-foot altitude.

Beyond the Earth's Atmosphere

Because of the imperfectly known and potentially important interactions between the space environment and spacecraft structures and materials, a number of satellites should be utilized soon to study these interactions. The emphasis in this area needs to be upon the engineering aspects of structural response to the environment, not simply upon the determination of the environment per se. Problem areas to be particularly investigated include:

(1) Measurements of meteoroid penetration and erosion.

(2) Erosion by sputtering.

(3) Effect of radiation and hard vacuum on material properties, particularly fatigue strength.

(4) Effects of radiation and hard vacuum on friction and lubrication.

Environment of Other Planets

(1) Before landings can be made safely on other planets, the characteristics of their atmospheres and surfaces must be determined in sufficient detail for use in engineering design.

Environment Control.- Once the environment has been established, means must be found to design vehicles which are capable of operating in this environment without damage to themselves or their contents. Some problem areas are sufficiently well established that immediate research is called for. Among the latter are:

Within the Earth's or Other Planetary Atmosphere

(1) Development of wide-band thermal protection systems to permit a significant broadening of the flight corridor.

In Space

(1) The determination of shielding requirements for protecting biological payloads and the integration of such requirements with other functions of the structure.

(2) Protection of structural elements from hypervelocity impacts from meteoroids and micrometeoroids.

(3) Protection of the structure from material erosion due to sputtering and the effects of hard vacuum.

(4) Evaluation of effects produced because the hard vacuum, erosion, and radiation may occur simultaneously.

Configuration Studies.-

Atmospheric Flight Vehicles

(1) Optimization of structural configuration, trajectory control, and thermal protection in order to reduce the aerodynamic heating.

(2) Determination of the most efficient hot and cold load-carrying structures of all types including structures of high-temperature metallic fabrics.

(3) Optimum structural configurations for large boosters including fabrication, transportation, and erection considerations.

(4) Determination of best methods of diffusing concentrated loads into thin shell structures.

Space Vehicles

(1) Determination of desirable structural configurations for low-density structures of large surface areas such as large antennas, reflectors, and solar sails, particularly those to be erected in space.

(2) Development of new energy-absorbing systems for landing and evaluation of such systems relative to those now available.

Analytical Methods and Design Allowables.- The areas that have been identified here as requiring great improvement in methods of analysis and in methods of determining allowable values for design are in five categories:

Thin Shell Construction

(1) Stability under all forms of combined loadings, particularly for extremely large diameter-to-thickness ratio shells.

(2) Stress diffusion of concentrated loads into thin shell structures, taking into account effects of large deflections and internal pressure.

Strength of Pressure Vessels

(1) Determination of the mechanics of failure so as to permit correlation with known mechanical properties of materials.

(2) Determination of fail-safe design approaches to avoid catastrophic failures.

Fatigue

(1) The fatigue problem is not new, but despite the effort which has already been devoted to it, no satisfactory methods of predicting the fatigue life of the structures of vehicles are yet available or even in prospect. The fact that the outlook is dismal here does not mean that less effort should be directed toward the solution of the fatigue problem. Rather, increased emphasis is required, and, as recommended in reference 15, an effort should be made to bring the best talent from diverse but relevant fields to bear on the problem in a concerted fashion.

Design Optimization for Minimum Weight

(1) Underlying principles for the design optimization of the various categories of high-speed aircraft and space vehicles must be established, suitable analysis procedures developed, and new configurations invented.

(2) Optimization should be extended to include not only the major structure but also the subsystems such as guidance and control, propulsion system, hydraulic and electric equipment.

L
1
2
2
4

Design Criteria

(1) Design criteria require reexamination to provide both concepts, and techniques for their application, which will have more universal validity for the complex environments of advanced flight vehicles than the simple "factors of safety" of past practice.

An implicit result of this survey is the negative one that there are many problems in the fields of analytical mechanics which are not immediately critical to structural design. General basic research in analytical mechanics should be continued, but the five problem areas indicated above are those of greatest urgency. Astute direction of research effort must weigh the value of easily won advances in problem areas of secondary importance, as against the (possibly small) returns which may be anticipated only at great cost in some of the newer but extremely important problems delineated here.

II. Required Research Facilities and Flight Tests

Ground-Based Facilities.- New ground-based research facilities are needed to provide adequate simulation of the various hazards of the space environment as follows:

(1) Hard vacuum. Vacuum chambers of sufficient size to permit testing of realistic structural components of assemblies, not simply of small materials specimens, are required. The vacuum should be "hard" enough to reproduce surface phenomena actually encountered in space.

(2) Heating and cooling. An essential part of space environment simulation is the reproduction of the heating and cooling of sunlight and cold space. These thermal conditions must be producible in conjunction with a hard vacuum.

(3) Hypervelocity impact. The development of a "gun" is required capable of firing simulated meteoroids at velocities substantially in excess of 20,000 feet per second.

(4) Energetic particles. A proton accelerator is needed to give 400 Mev particles in reasonable fluxes in a chamber of sufficient size so that shielding systems can be studied with validity.

L1224

The latter two items present difficult problems which extend beyond the capabilities of presently available apparatus. Aggressive studies aimed at the achievement of the required facilities are recommended, and the sponsorship of heavy expenditures required for the construction of the facilities is endorsed.

Flight Test Facilities.- In addition to the new ground-based facilities, flight testing of structures and materials is required in order to investigate their behavior under environmental conditions that cannot be adequately simulated on the ground. Two areas are of particular importance:

(1) Recoverable satellite laboratories to study the behavior of structures and materials in space. These studies, requiring large area exposures, advanced telemetry techniques, and a reliable recovery system should be implemented immediately, concurrently with scientific studies of the space environment for other than structures and materials research.

(2) Lunar and planetary probes. In order to establish the atmospheric and surface environment of the moon and the planets, data collecting probes to these extra-terrestrial bodies are essential. Our present television and telemetry techniques are sufficiently advanced so that significant information can now be obtained, and increased efforts along these lines should be encouraged.

(3) Rockets and missiles designed for reentry data. Ground simulation of the severe environmental conditions during reentry at superorbital velocities is presently impossible. An accentuation of the present effort to obtain flight test data is vitally needed.

It is strongly recommended that the above flight test programs be established immediately and that sufficient manpower and funds be allocated so that early realization of the objectives is assured.

III. Integration of Research on Structures and Materials

The interrelationships between structures and materials as evidenced throughout the appendices to this report are such that the two can seldom be considered separately. The most substantial advances now to be expected in the structures of airborne and space vehicles are believed to be those that will be achieved by both the development of materials of improved or selected structural characteristics, and by the design of structures to utilize available material properties most effectively. Although materials and structures can still be considered separate research disciplines, free interchange of information between them for improved knowledge and understanding of mutual problems is essential. It is therefore recommended that a continuing program of cooperation between structures and materials research personnel be established and maintained.

L1224

Specific areas in which improvements in structural materials and their application are needed are:

(1) The structural utilization of refractory materials for sustained exposure to high temperatures.

(2) The development of materials applicable to "wide-band" thermal protection systems.

(3) The development of structural and insulation materials for cryogenic tanks.

(4) Improved utilization of whiskers, foils, flakes, and advanced fibers in composite materials.

(5) Development of structural materials of reduced density.

ASSIGNMENT OF PRIORITIES

To some degree the relative importance of various problems described is implied by the treatment given them in the accompanying text. Because some problem areas are considered of especial urgency, however, these are so designated here, and their relative priorities established as follows:

<u>I. Top priority</u>.- The recoverable satellite laboratories (described on page 7 under "Flight Test Facilities"), which will provide data applicable to the design of all future spacecraft, are given first priority. Of nearly the same urgency are the ground-based facilities (page 6) needed to help translate from these data into design procedures.

II. Very high priority.- Several problems relating to the design of pressure vessels have next priority. These problems include studies of mechanics of failure, establishment of adequate design and fail-safe criteria (pages 5 and 6), and the development of materials and techniques appropriate for the containing of cryogenic fuels (page 8).

III. High priority.- To a degree all of the remaining problems singled out for attention in the section entitled "CONCLUSIONS AND RECOMMENDATIONS" are considered of high priority. At, or near the top of the list, however, is the class of problems which are combined under the heading "fatigue" (page 5 and ref. 15) and the specific problem of shielding biological payloads from the ionizing radiation encountered in space (page 4).

NASA Headquarters,
Washington, D.C., June 22, 1960.

APPENDIX A

MEMBERS OF THE NASA RESEARCH ADVISORY COMMITTEE ON STRUCTURAL DESIGN

Professor E. E. Sechler, Chairman
California Institute of Technology

Mr. Lewis H. Abraham
Douglas Aircraft Company, Inc.

Mr. Norris F. Dow
General Electric Company

Mr. Lester K. Fero
The Martin Company

Mr. Christian M. Frey
United Research Corporation

Mr. David Lee Grimes
Narmco Industries, Inc.

Dr. Nicholas J. Hoff
Stanford University

Mr. William R. Micks
The RAND Corporation

Dr. John C. Moise
Aerojet-General Corporation

Professor Paul E. Sandorff
Massachusetts Institute of Technology

Mr. Robert S. Shorey
Convair - Astronautics
Division of General Dynamics Corp.

Mr. E. H. Spaulding
Lockheed Aircraft Corporation

Mr. Erich E. Goerner
Army Ballistic Missile Agency

Mr. Ralph L. Creel
Bureau of Naval Weapons

Mr. William B. Miller
Wright Air Development Center

L
1
2
2
4

APPENDIX B

ENVIRONMENT

The environment in which the vehicle operates, as well as the mission it performs, together determine the design conditions and requirements. Engineering of the vehicle can be no more precise than the definition of the environment. This section of the report is concerned with the delineation and evaluation of the characteristics of the environment, as they affect the engineering problems of the vehicle.

Planetary Atmospheres

The atmosphere of the earth.- There are still many characteristics of the earth's atmosphere which have not been adequately evaluated. The evaluation of some of these characteristics is a matter of urgency for the structural design of aircraft, boosters, and reentry vehicles. The characteristics of the atmosphere and the atmospheric interactions with vehicles which need investigation are:

(1) Turbulence characteristics both at extremely low altitudes and at altitudes between 50,000 and 400,000 feet. Deviations to be expected from standard conditions should also be evaluated.

(2) Propagation characteristics of jet, rocket, and boundary-layer noise fields through the atmosphere at various altitudes to determine what future aircraft, boosters, and reentry vehicles must withstand.

(3) Statistical data on load-time-temperature histories (including buffeting loads) for all types of aircraft and in all flight regimes, including particularly empennages for all aircraft, high-performance aircraft generally, and large propellers for the deflected slipstream type VTO aircraft.

(4) Populations and intensities of energetic particles and ions above 50,000 feet, defined with regard to their vectorial nature and distribution temporally as well as spatially, and including definition of range of transient phenomena such as those due to solar flares. (This includes definition of the Great Radiation Belts.)

(5) Characteristics of radiative heat transfer from the ionized gas cap associated with reentry at superorbital velocities, and correspondingly the detailed transport properties, and chemical activities that may be expected.

(6) The physical properties and composition of the atmosphere out to perhaps 4,000 miles, or where the earth ceases to be a dominant influence, including departures from spherical symmetry, diurnal variations, variations with solar activity, etc.

Other planetary atmospheres.- Physical properties of the atmospheres of other planets at various pressure-temperature conditions are not available. For the design of vehicles for operation in other planetary atmospheres, as a minimum sufficient data are needed regarding compositions, temperature and density profiles, etc., to permit design based on valid determinations of the thermodynamics of entry and of the mechanics of flight. Thus, for example, data are needed on:

L
1
2
2
4

(1) Composition, temperatures, densities, and physical properties (specific heat, coefficient of viscosity, transport properties) vs. altitude.

(2) Velocity structure-turbulence characteristics at all altitudes.

Solar Space

The environment of space presents hazardous conditions which are beyond present engineering experience, and in many respects are not yet clearly definable (ref. 16). Of major importance is an accurate and thorough description of the space environment.

The "hard vacuum" of space is one aspect of this environment which at the present time is difficult to assess, because it contributes to an unknown extent in combination with various other factors to a number of damage mechanisms. These problems will be discussed later under Environment Control. The present section is concerned with quantitative considerations of what is found in the "hard vacuum."

Space environment, of course, extends into the planetary atmosphere environment and the separation of the two is at present only arbitrary.

Electromagnetic (thermal) radiation.- The spectral character and strength of solar radiation is in general well defined. Galactic radiation in space, however, is not at all accurately defined, either as to spectral character, intensity, or variation with source direction; this information may be significant to the basic design of cryogenic tankage and thermal-sensitive systems. Characteristics of the radiative energy arising from the albedo of the earth (and other planets) and reemitted by the earth in degraded form, can at present be only poorly estimated, particularly with respect to intensity variation, directional character, and distribution. This component of radiant energy can be of major importance to the thermal balance and consequently the structural design of a planetary satellite. The spectral characteristics of radiant energy are especially significant to the material properties of such structural materials as plastics, elastomers, surface finishes (paints), organic materials, lubricants, and nonconducting materials in general. The following information is therefore needed.

(1) Quantitative determination of the quality, intensity, and vectorial properties of electromagnetic radiation (light and thermal energy) reflected from and emitted by the earth, including variations introduced by diurnal effects, latitude, and cloud cover.

(2) Similar quantitative information on electromagnetic radiation of other planets.

(3) Sufficient data regarding characteristics of galactic or background thermal radiation so that its significance can be properly assessed.

Atomic particles (ionizing radiation).- The chief constituents of space are the protons and electrons which compromise the solar atmosphere; they have been described as comprising a low-density gas. Definition of the motion (or "temperature") and particle density is required throughout the solar system, and the manner in which these properties may be affected in the vicinity of planets. Planetary magnetic fields therefore may enter importantly into structural considerations. Of utmost concern, however, are quantitative data regarding the character, intensity, and spatial distribution of the ions which may be encountered during solar flares. A third source of energetic atomic particles is the cosmic rays. From a structural standpoint the primary cosmic rays do not appear important at the present time. However, the ionizing radiation of solar flares, and the secondary radiation produced by cosmic rays, are considered of major significance in the problem of manned flight in space, and are therefore important in the structural aspects of protective designs. Solar flares and cosmic rays are believed to be the source of the high energy ions in the Great Radiation Belts.

Extended exposure to ionizing radiations produces important effects on the mechanical properties of plastics and organic materials. In combination with high vacuum, it causes sputtering erosion of metallics and nonmetallics which can produce fairly rapid changes in surface properties and may compound the surface effects of vacuum alone. Current estimates of the sputtering effect are highly approximate, and the effects on nonmetals are poorly understood. The following research is indicated.

(1) A quantitative description of the "solar atmosphere," the gaseous envelope which pervades the entire solar system, identifying composition, particle density, thermal motion, etc.

(2) Quantitative, possibly statistical description of the ionizing radiation to be expected during solar flares, identifying composition, particle density, and vectorial characteristics of the flux.

(3) A study of the strength and the significance of secondary radiation effects which may be produced by incidence of cosmic rays and high energy ions on various structural materials and configurations. This project could conceivably be carried out with a ground-based facility providing high-vacuum conditions and a high-energy proton source.

Macroparticles: meteoroids and micrometeoroids.- Characteristics of the dust and small particles found in space and in the outer regions of the earth's atmosphere, which must be determined to fill the needs of structural design, include data on size, mass, magnitude, and vectorial nature of velocity, the chemical, physical, and structural composition, and the distribution of all of the various characteristics throughout space. Data currently available are based almost entirely on statistical studies of meteors and meteoritic accretion, and justifiable estimates vary by several orders of magnitude (ref. 17). Only inferential data exist on important properties such as density and chemical composition.

Before space flight enters upon an advanced stage, this component of the environment requires more accurate definition in all respects. A certain amount of information will undoubtedly be accumulated as a result of pick-a-back experiments and actuarial data. The design of satellites specifically to obtain meteoroid data, however, appears as an absolute necessity in the near future. These will differ fundamentally from other satellites because of the large size required to obtain data within a reasonable time. The following programs are specifically recommended.

(1) A study of methods whereby significant advances may be made in the task of obtaining data on the physical and the vectorial properties of meteoroids and the distribution of these properties in space.

(2) The design of satellites specifically to obtain knowledge regarding the characteristics of meteoroids of structural significance, and the implementation of a satellite program with this objective.

Landing Conditions

Landing conditions of interest on earth may vary from those for well-paved runways to those obtained in a ditching in rough areas. The conditions here are known; additional data are still presently needed, however, on the ground loads associated with the landing of aircraft, and also on the loads induced in the ground handling of vehicles of all types.

For the design of landing devices for interplanetary vehicles, information is needed on physical and mechanical properties of the surface to be landed upon. The required landing configuration may be sensitive to the surface properties. For example, in the case of soft, semifluid or loosely packed dust surfaces, an extremely large contact area may be required. Initial information on surface conditions requires probes to the various planetary bodies considered for landing.

The following research work is therefore required:

(1) A program must be established to obtain information on the physical and mechanical properties as well as the topography and local irregularity of planetary landfalls.

APPENDIX C

ENVIRONMENT CONTROL

In contrast with appendix B, which is concerned with delineation of the properties of the environment important to structures, this section treats problems which arise in connection with the control of environmental factors.

L
1
2
2
4

Thermal Protection

The problem of providing the capability to withstand high temperatures and heating rates has already received much attention. A great deal of work has gone into the search for and the evaluation of materials with high specific heat, high "heats of ablation," materials with useful properties both at high and at room temperatures, etc. This research has resulted in a number of developments that are successfully used in current hardware.

Accordingly one may ask, "What is needed other than improved properties across the board?" and, "Are there specialized areas in which further research effort can be profitably directed?" To provide a basis for the needed answers, one may make reference to the type of presentation used by Heldenfels in reference 18, where maximum heat flux is plotted against total input.

Such a plot can be used to map the heating experienced by various types of vehicles and to show the areas of applicability of various types and weights of thermal protection systems. The vehicles of interest range from the intercontinental ballistic missiles which plot on the chart at very high heating rates through various forms of manned reentry vehicles at intermediate rates to the long duration supersonic and hypersonic aircraft at the lowest heating rates. As the heating rates become lower, the general tendency is for the total heat input to increase; however, advanced design trends for all vehicles increase both the heating rate and total heat input. If the range of applicability of developed thermal protection systems is also included on such a plot, it is immediately evident that there are large areas of heating experienced during manned reentry from satellite and supercircular orbits that are yet to be explored.

Protection by trajectory control.- Clearly one aspect of the problem involves the question of how best to control the heating problem through the use of variable lift, drag, and thrust, so that an optimum design compromise is achieved. (In addition, knowledge of such other design conditions as properties of the atmosphere, required limitations on deceleration, etc., are involved.) To assist the designer in this problem, parametric relationships might be developed to show how much and in what way the temperature-deceleration environment could be altered by different lift-drag programs. Information is also lacking on the capability of different types of trajectory control measures, such as inflatable lift or drag devices, kites, and erectable structures.

Consequently, the following research work is indicated:

L1224

(1) The development and assessment of methods of trajectory control to reduce aerothermal heating.

Protection by heat absorption and radiation.- Although some control over heating rate history is obviously possible, flexibility of the heat protection system is necessary to allow for errors and uncertainties, and the question of "wide-band" heat-protecting systems becomes important. Hence, the second aspect of the problem of thermal protection, namely, incorporating into the vehicle the capability of withstanding the thermal environment.

Typical heat-sink systems, such as beryllium (from ref. 18) have limited capability both as regards the maximum rate at which they can accept heat for even very short times and as regards the total amount of heat a reasonable amount of material can absorb. Ablation as a means of thermal protection has received much attention recently. However, the ablation mechanism is still the source of problems of a fundamental scientific nature, and under extreme conditions of density, velocity, and heat flux, there is a continually expanding need for development of the engineering aspects of ablation. Current ablation systems that are effective at high heating rates are less effective (or inapplicable) at low heating rates. Reradiating type systems designed for long times at low heating rates will not accommodate high heating rates even briefly. The delineation of the true capabilities of each of the various systems is an important area for research. In many cases analysis indicates that combination systems offer the best hope for achieving lightweight solutions.

As an example of the importance of coordinating the structures program with research in materials, the outstanding potentials of graphite as the basis of a wide-band heat protection system may be cited. The long-recognized possibilities of this material have not materialized. It is time for a critical review of work in this area, possibly to redirect some portion of the effort. Foamed ceramics and certain composite materials, for example, (some of which offer new possibilities as insulation to be used with graphite) deserve investigation.

Still another type of heat-protection system, deemphasized in recent years, is that of mass transfer cooling by transpiration, or methods other than ablation. Such methods may find special advantage in application to controlled-flight vehicles because of the problem of maintaining aerodynamic contours. A particularly severe requirement of this type arises at the sharp leading edge of lifting surfaces of long-range glide vehicles.

A potentially lightweight method of thermal protection for manned reentry vehicles is radiation cooling. In this method the high temperature outer surface reradiates most of the aerothermodynamic input. Successful development of radiation cooling, however, is vitally dependent upon development of high-temperature refractory materials and the integration of these materials into a suitable structural design. The exposed surface must have adequate aerothermoelastic integrity, and sufficient insulating capacity must be included to protect the underlying load-carrying structure. Present technology does not permit the construction of such heat shields for reentry vehicles except for low-wing-loading gliders. Additional research on heat shields of refractory metals and ceramics should lead to lightweight designs suitable for manned reentry at superorbital velocities.

In summary, problem areas deserving of attention are listed as follows:

(1) Refinement of methods of evaluation and design for heat sink, ablation, and radiative cooling as means of control of aerothermal heating.

(2) Extension of experimental and theoretical studies of the ablation mechanism, particularly into regimes of higher velocity, lower density, and higher heat flux.

(3) Reevaluation of transpiration cooling as compared with ablation, for applications where aerodynamic contours must be preserved.

(4) Assessment of progress in materials research in such areas as development of graphite and other refractories for broad-band heat protection systems, for purposes of redirecting effort along most profitable lines.

Hot structures.- When designing any structure for aerodynamic heating, a basic decision must be made on the maximum allowable temperature of the load-carrying structure. In the case of supersonic aircraft, the temperatures need not exceed the capabilities of materials suitable for an unprotected hot structure. For higher performance vehicles, particularly those used for reentry, some form of thermal protection must be incorporated. For example, the X-15 aircraft has a hot nickel-alloy structure attaining a maximum temperature of 1200° F, which utilizes limited thermal protection in the form of radiation cooling and heat capacity in the structure. Vehicles experiencing more severe heating might incorporate radiation shields of high-temperature capability, or absorption systems such as transpiration cooling or ablation. Analysis of many vehicle configurations shows that the hot structure concept which incorporates a limited amount of protection is often competitive weight-wise with a cold water-cooled and/or insulated structure that is fully protected. The range of applicability of the hot structures approach can be extended as solutions to the problems listed below are found:

(1) Forming and joining methods of high-strength, heat-resistant and refractory materials should be explored, and suitable inspection techniques determined.

(2) Composite structures for high-temperature applications, including the use of refractory metals imbedded in ceramics, should be developed.

(3) Detail design concepts for hot, load-carrying structures that minimize thermal stresses and distortions should be evaluated. For example, means of controlling thermal buckling for thermal strain relief need to be investigated.

(4) Thermal and mechanical properties data for the promising high-temperature structural materials must be extended up to their melting points.

Temperature Control

The problem of controlling the temperature within vehicles - maintaining a comfortable climate for passengers, dissipating heat from the operation of equipment, keeping cryogenic fuels cold - is to some extent a structural one. The vehicle shell may have to serve as a proper thermal medium, insulating against cold or heat, or conducting and radiating away any excessive heat generated. Thus the structural designer may need to consider such factors as the creation and preservation of proper radiating surfaces. Two essentially different functions must be considered: (1) thermal insulation, and (2) heat dissipation.

The thermal insulation problem in turn may be divided into two classes. With hot structures and heat shields, improved lightweight refractory insulation materials are needed, capable of being utilized at extreme temperatures yet possessing low-density and low-thermal conductivity. The possible use of insulating materials for carrying structural loads needs to be explored. Similarly the thermal insulation characteristics of ablation materials need improvement; for example, possibilities and performance of a foamed ablating plastic should be investigated.

In the field of cold structures, the insulation of tanks for cryogenic fluids introduces problems of three kinds: (1) those associated with ground readiness, (2) those for flight through the atmosphere, and (3) those in space. For fluids like hydrogen, a suitable form of insulation must be provided for both ground readiness and flight within the atmosphere. The flight insulation can be augmented during ground readiness in the form of a removable outer structure which drops away at launch. The flight insulation requires a wide range of properties, which include very low weight and thermal conductivity, integrity under local air loads, capability of withstanding the high temperature resulting from aerodynamic heating, and it must be impermeable to air to eliminate the possibility of air condensation within the insulation. For space vehicles, the combination of insulation with meteoroid protection should be considered. Possibly the insulation should be designed as load-carrying structure. Space flight of long duration may require long storage of cryogenic liquids. A different type of thermal protection is required in the form of multiple radiation shields spaced so that the shields can dissipate to space solar energy they receive. Such shields will probably require erection after the vehicle is in orbit, and the possibility of shadow shields with changeable orientation that follow the sun is suggested. Heat leakage within the structure will also be important so that low conductivity materials, multiple walls, and minimization of heat paths must be utilized.

L
1
2
2
4

Types of composite structures to fulfill the various requirements should be investigated. Material selection and development must play an important role in the resulting designs - indeed, the material considerations may have an overriding influence in some areas. Techniques, materials, and novel methods for performing the required temperature insulation function should be explored and evaluated.

Heat dissipation problems become of major importance in some space vehicles. The lack of atmosphere requires that the mechanism of heat dissipation from the vehicle be by radiation, hence contributions in the area of determination of thermal emissivities of materials suitable for radiating surfaces will be valuable. The possible variations of absorptivity and emissivity with time, temperature, and erosion in space are needed.

The space radiator, which will be an integral part of many space propulsion and auxiliary power systems, presents many interesting problems in structural configurations in addition to the materials problems just mentioned. Research is needed to develop optimum configurations including considerations of erectability and damage prevention and control for such devices.

Consequently, the following research effort is indicated:

(1) The possibilities of developing multipurpose materials which would combine structural functions with those of insulation, ablation, radiation shielding, and meteoroid protection should be explored.

(2) Studies of composite materials should be promoted.

(3) The surface properties of materials and the effect of space environment on radiative characteristics require investigation.

(4) Structural configurations for space radiators should be studied.

Acoustic Excitation

The problem of acoustic excitation (which has already received some consideration because of research required in defining energy transmission in the atmospheric environment) also deserves considerable attention from the viewpoint of the structural effects produced. This problem is aggravated in the case of the enormous boosters for space vehicles now under development. Such excitation will be capable of inducing failures even in substantial structural elements.

Inasmuch as many space vehicle components must be extremely flimsy, there is a great danger of their failure to survive launching. Because launching of the space vehicle may occur at altitude, the effects of noise at altitude as well as on the ground must be evaluated. Studies of this problem should be coordinated with studies of noise effects on boosters and tanks, ground support equipment, and personnel, and are directly related to the need for improved noise suppression techniques for passenger and citizen comfort.

Because of the importance of these problems, the following effort is needed:

(1) Develop and evaluate structural arrangements with improved resistance to acoustic excitation and fatigue, as by the provision of increased internal damping either from the configuration or within the material.

(2) Develop adequate acoustic proof-tests for assuring structural integrity.

(3) Pursue a program of study of the methods of noise generation and propagation.

(4) Investigate the possible interaction of structure-borne noise and vibration of the ultrasonic level with the environment of space and/or corrosive propellants.

Space Hazards

Effects of meteoroids.- Probably the principal source of structural damage in space will be meteoroid penetration. The effects of extremely high-velocity impact can cause catastrophic failure of a pressurized vessel. High-speed penetration into a propellant tank may be disastrous, even if the primary damage is not, and therefore protection may be the first design objective.

The problem of collision with meteoritic particles in space has received considerable attention from a research standpoint. Simulation of meteoroid impact on the ground using high-explosive and light-gas-gun accelerators has yielded tentative information on some of the mechanics of penetration. Theories of penetration, however, are in substantial disagreement with one another, and ground-based accelerators are incapable of the true hypervelocities needed to simulate those of meteoroids and verify theoretical predictions. Many questions related to meteoroid impact are evidently yet to be answered.

The time is ripe for actual studies in space of the meteoroid impacts actually encountered. These studies should include investigations of the mechanics of impact, of the effectiveness of multiple walls and various materials as "bumpers," and of the effects of erosion from longtime exposure to the micrometeorites in the solar system. Ideally, the results of these investigations should be related to concurrent measurements of the numbers and sizes of meteoroids encountered, and their velocities. Emphasis must be placed on the use of recoverable vehicles or capsules for these studies in order that the damage produced, which is extremely complex in character, may be properly assessed.

Because definitive solutions to the meteoroid impact problem will be needed, the expenditure of appreciable effort toward the development of a ground-based gun capable of realistic impact velocities is justified. Present guns can produce velocities which are barely comparable to the speed of sound in the structural materials, and there are reasons to believe that the changes in the mode of impact cratering which occur when the speed of sound in the material is exceeded would be of extreme importance. An adequate gun would be useful not only for the meteoroid problem but also for studies related to the vulnerability of space vehicles to various kinds of "shrapnel." In the long run the cost of development of such a ground-based facility may be less than that of space probes required to attain the same objectives.

As a result of the foregoing considerations, the following research programs are urgently desired:

(1) Satellite experiments are required for the study of the mechanics of meteoroid damage by exposure of test surfaces of various design and construction to actual conditions, with eventual recovery.

(2) A ground-based facility must be developed for conducting hypersonic impact experiments at several times the speed of sound in structural materials.

(3) A vigorous attack must be continued on the problem of damage by meteoritic impact, with the object of identifying the various damage phenomena and the parameters which govern them.

(4) The possibility of manufacturing materials having appropriately scaled-down mechanical properties, in order to permit model tests of the hypersonic impact phenomenon, should be investigated.

(5) Experimental investigations should be conducted on the effects of hypersonic impact, for both penetrating and nonpenetrating particles, on propellant tanks to identify the design problems which meteoroid impact presents in this case.

(6) The development of self-sealing methods for space cabin designs should be promoted.

<u>Ionizing radiation</u>.- Recent disclosures that the ionizing radiation in space during solar flares may be comparable in both character and intensity to that in the inner Van Allen Radiation Belt (consisting of protons having energies up to 400 Mev and more, and electrons of somewhat lower energies) have made it clear that for manned space vehicles, radiation shielding is a very serious design consideration. At the radiation intensities that have been measured, man cannot long remain unharmed without heavy shielding between him and space; similarly, structural materials that are organic or nonmetallic may also be degraded by long exposure. It can be shown that the most effective shielding material for energetic protons is hydrogen; how to utilize hydrogen atoms effectively as a structural material requires study. Solutions to this radiation problem may require the use of electrostatic or magnetic shielding in addition to material shielding, and the structures designer may have to work with engineers in several other fields to develop a reasonable structural system. Similar problems

will develop in the design of shielding for nuclear reactors when they are carried aloft. Obviously the research effort required here is substantial.

For metallic materials, ionizing radiation at the levels measured in space will not produce body damage or internal effects (i.e., material strength changes) of any consequence. However, it may affect surface properties, particularly in combination with high vacuum. Erosion by sputtering has been calculated to be as great as that from micrometeorites.

One type of radiation whose importance is sometimes not given sufficient consideration is that from a nuclear explosion in space. The vulnerability of spacecraft to radiation from nuclear weapons, a matter of primary concern to the Department of Defense, needs to be determined. For protection against this type of radiation, the effectiveness of multiwall construction deserves to be evaluated.

L
1
2
2
4

Because intense solar flare radiation has been measured at altitudes as low as 100,000 feet, the effects of radiation must be factored into the design concepts of many kinds of vehicles, particularly those which carry human beings. The following areas for research are accordingly considered urgent:

(1) The development and evaluation of structural concepts as they apply to and interact with the problems of internal and external shielding of cargo compartments and crew against ionizing radiation.

(2) The determination of the allowable strength properties and surface properties of metallic and nonmetallic structural materials subjected to ionizing radiation, especially in combination with such additional factors as vacuum and the full spectrum of solar electromagnetic radiation.

Hard vacuum.- The hard vacuum of space is known to change the response of structures by permitting changes in surface conditions of materials. The most spectacular effect is the one of self-welding of materials in contact in vacuo duro. Another surprising effect is the possible marked increase in thermal resistance across joints in a high vacuum. Outgassing of some materials improves their resistance to fatigue and creep (ref. 4). However, vacuum effects are more generally apt to be harmful, particularly for materials like the aluminum alloys which within the earth's atmosphere always have an oxide coating, or which are artificially protected by surface finishes or paints. In space the erosion from meteoroids and sputtering by ions may remove this coating with marked effects upon such properties as (1) the absorptivity-emissivity ratio, important to the problem of temperature control, and (2) the rate of crack propagation and nature of brittle fracture of structures, possibly of major importance in the design of pressurized cabins and pressure vessels.

Under high vacuum conditions, sublimation rates of all materials are much greater because the blanketing effect of the atmospheric gases is not present. Sublimation for many plastics, and even for some metals, may be a serious structural consideration, depending upon the temperature, the initial thickness, and the time of service. As yet, there are few experimental data on such effects, and none which includes possible contributing influences of radiation or micrometeoroids.

These problems overlap into the field of materials research, but because of their relevance to the structural performance of space vehicles they must also be considered as problems for structures research. The immediacy of these problems is evidenced by the fact that the determination of the lifetimes in space of the large inflatable spheres soon to be placed in orbit by the NASA depends in part upon the understanding of these interrelated phenomena.

The vacuum of space also raises problems in fatigue. These problems may be associated with acoustical excitation or random vibrations induced by equipment within the vehicle, possibly aggravated by the lack of atmospheric damping external to the vehicle. Data are available (ref. 4) that show substantial effects of vacuum upon fatigue life. Certainly the entire fatigue problem is still in a sufficiently imperfect state, however, that the effects of a superposition upon it of the various hazards of the space environment will require extensive investigations.

In summary, need for the following research programs is indicated:

(1) Large-sized ground-based facilities should be developed for simulating the hard vacuum of space in combination with various other environmental effects, in order to explore the interaction of this element of the environment with other phenomena affecting material properties and structural response.

(2) Allowable strength properties must be determined which are pertinent to possible modes of failure for metallic and nonmetallic structural materials under space environment conditions, particularly the combination of hard vacuum, electromagnetic radiation, ionizing radiation, and meteoritic abrasion.

(3) Surface properties of structural materials and protective coatings which are significant to their structural performance must be determined under space environment conditions. These

include radiative characteristics, erosion and sublimation, crack propagation and brittle fracture characteristics, and possibly others.

(4) The effects of the space environment on the behavior of structural materials under fatigue loading must be investigated.

L
1
2
2
4

APPENDIX D

CONFIGURATION STUDIES

This section will be devoted to problems related to the strength and efficiency of structural or vehicle configurations, and comparisons (from a structural design standpoint) of the relative merits of various configurations. In this section it is not always possible to separate structural considerations from the design aspects of the vehicle.

Aircraft Configurations

Traditionally the structural designer has had only a secondary influence on vehicle configuration. Now, for some types of vehicles the structural problems have become so severe that the relation between overall configuration and structural response can not be ignored. Appropriate research effort is indicated in the following areas in order to properly assess these interacting effects and to ensure design of overall high efficiency.

(1) Determine by generalized analysis the "trade offs" between severity of aerodynamic heating and configuration for supersonic and hypersonic aircraft. Inasmuch as the primary limitation on the development of vehicles for high-speed flight within the atmosphere is thermostructural, a parametric study of this nature would go a long way to guide the direction of further emphasis.

(2) Investigate aerothermoelastic characteristics of various structural configurations suitable for high-speed vehicles.

(3) Investigate structural configurations and requirements for boundary-layer control designs.

(4) Investigate structural configurations and requirements for variable sweep aircraft useful in the low supersonic range.

(5) Evaluate configurations suitable for hot, load-carrying structures, and compare with other approaches to the thermal problems.

Launching Vehicles

Overall configuration.- A problem of high complexity and considerable importance is the proper choice of tank diameter and fineness ratio for large rocket booster vehicles.

Superficial extrapolations of rocket design to large sizes involve the assumption of geometric similarity, resulting in predictions of structural weights based on the law of squares and cubes that have influenced some sources to discount the potentialities of large-size rockets. The real problem facing the designer is the determination of the geometry best fitted for the new conditions. Involved in the design decision are: considerations of the effect of vehicle fineness ratio on aerodynamic loads; thrust loads and the effect of thrust-to-weight ratio on trajectory and aerodynamic considerations; problems of structural flexibility and propellant sloshing and their interaction with control system dynamics.

By no means unimportant are the as yet poorly defined problems of fabricating tank structure of unprecedented size and transporting it to the point of launch. Current design of large boosters reflects a willingness to accept structural penalties of clustering instead of fabrication problems of optimum-size tanks. Suitable engineering data on which to base such decisions requires a thorough engineering attack not only on the structure of large tanks but on the interrelated problems of aerodynamic loads, trajectory, drag losses, vehicle response, and control system dynamics. The same general remarks apply for recoverable systems.

L 1 2 2 4

Interstage structure.- In large launching vehicles such as Saturn, considerable weight is represented by the thin shell interstage structure whose sole function it is to transmit thrust loads over the engine bay of the succeeding stage. Shape requirements are such as to invite consideration of internal pressure for stabilization, and space otherwise wasted might be efficiently employed by annular tankage. Studies should be made of the analytical and fabricational problems of tank structure and pressure stabilized structure of such unusual shape and purpose.

Engine mount structure.- Some estimates place the weight of engine mount structure for large launching vehicles at as high as 30 percent of the weight of the tanks. This weight is due in part to the fact that the thrust reaction which occurs over the large area of the nozzle and is first concentrated by the engine structure at the gimbal point, must again be redistributed over the large area of the tank bottom. Bold new concepts may find a more satisfactory overall design compromise. The possibility of a pressurized engine bay which would transfer thrust reaction directly into the tank bottom should be studied. The penalties of nonswiveling engines should be reassessed. Structural arrangements for mounting plug engines should be appraised, and the structural weight aspects incorporated into design evaluation of such engine types.

Research recommendations.- In view of the foregoing, the following research studies are recommended:

(1) Size effect studies should be made which will permit valid estimates of the structural configuration and weight of large

boost vehicles, ranging up to 10^7 pounds vehicle take-off weight. These studies should be based on consideration of the overall design problem, involving optimum compromise, for each size, between the interrelated requirements of aerodynamics, trajectory optimization, vehicle response, and control system dynamics.

(2) The problems of fabricating and transporting large tankage structure should be investigated. On-site fabrication measures should be included.

(3) The possibilities of exploiting internal pressure as a load-transmitting medium should be thoroughly investigated, particularly for such structurally expensive applications as engine mounts and interstage structure.

(4) The problems associated with design and fabrication of membrane structure of unusual configuration warrant special study.

(5) An evaluation study is needed on the relative merits of stacking small tanks as in the Saturn with alternative constructional methods for large size tanks.

Space Vehicles

Because the space vehicle does not have to satisfy contour requirements determined by aerodynamics, its configuration may be established in part by structural considerations. The influence of configuration on structural design is important in a number of areas; for example, the design of radiation shielding can not be divorced from the determination of the overall configuration. Several aspects are considered below.

Erectable structures of large surface area.- Space and reentry vehicles may frequently employ thin flimsy elements expanded in space in some manner to cover a large area. The 100-foot-diameter spheres soon to be put in orbit by the NASA provide one example of this type of structure. The problems associated with this type of structure have to do not only with the development of ingenious methods of erection in space, such as inflation, spinning, or opening like an umbrella, but also with the determination of ways of insuring the maintenance of the desired shape with some degree of accuracy.

The determination of suitable configurations for this class of structures can not be divorced from interactions with the environment. Inflated structures will be penetrated by meteoroids. Thin films will get rapidly hot and cold as they pass in and out of sunlight. Various types of radiation will bombard the material; hard vacuum will outgas it; in time the material properties may be degraded and the working surfaces welded together. Supplementing these problems is the one posed by the accelerations and vibrations of launching.

Many space structures applications require large-area erectable structures that are self-rigidizing, that is, once erected, their shape is maintained without help from an active system such as a continuous supply of pressurizing gas to make up for leakage. Self-rigidization may be accomplished with multilayer structures that include foaming materials that chemically react with the space environment to produce a stiff sandwich structure. An alternate approach might be structural configurations which, on inflation, form a stiff structural arrangement that needs no further attention. For some types of structures there can be large tolerances in the shape the vehicle assumes, but for other types such as those with solar reflectors very large surfaces with very small dimensional tolerances will be required. The problems associated with these types of structures accordingly have to do not only with the development of ingenious methods of erection in space, but also with the determination of ways of insuring the maintenance of the desired shape with the degree of accuracy required for the application.

In all erectable structures applications, very thin materials will probably be used with a need for incorporation of high-strength micron-size filaments in the basic materials. In any event, a comprehensive study is required to determine possible trade-offs among the many design approaches and configurations and thus to guide research efforts in structures and materials into the most profitable directions.

Space cabin design.- If manned space exploration is to proceed with the desired degree of safety, accurate methods for the design of reliable space cabins must be established. The weight penalties associated with even a minute leakage of the precious atmosphere from the cabin cannot be tolerated except on the shortest journeys. Materials and configuration must be selected which do not leak initially (through the material or around hatches and other openings) and which can be quickly and efficiently repaired when accidentally damaged by meteoroids or other objects. Furthermore, cabin structural design should be extremely tear-resistant so that punctures and dents which do occur do not increase in size. The desired space cabin must be fail-proof, not merely fail-safe.

Design for dynamic effects.- The dynamic structural response has an important effect on guidance, stabilization, and control of the vehicle. The designer is therefore usually faced with important requirements of structural rigidity. Because there are limitations on the stiffnesses that can be achieved, particularly for very large and flimsy structures, the control systems engineer may have to work with the structures engineer to adjust the principles and design of the guidance and control system to conform to the structural configuration. Perhaps of most immediate interest in the space vehicle field is the design of flimsy, erectable structures, such as large antennas, reflectors, or collectors which are subject to rapid, accurate attitude control.

Research recommendations.- The following research work is indicated for space and reentry vehicles:

(1) Design studies should be promoted on erectable structures of all types.

(2) Design studies are required to develop reliable, leakproof, and tear-resistant space cabin configurations.

(3) Experimental and analytical studies should be initiated on the modes and effects of vibratory oscillations of all types of structures, especially large, lightweight designs, simulating the free-free state in vacuo.

Reentry Vehicles

Reentry vehicle structures must either withstand or be protected from severe aerodynamic heating. This problem was discussed in part under ENVIRONMENTAL CONTROL; however, there are many alternate approaches to the vehicle structural design and configuration. Configuration research must integrate thermal protection systems with the structural design and trajectory control methods to determine the optimum vehicle configuration. Such studies would determine the total weight of various approaches, and be carried to the point where "trade-offs" are indicated. For example, manned reentry vehicles which use ablation for thermal protection employ a different configuration and reentry trajectory from those which use radiation cooling.

Another class of vehicles uses very lightly loaded structures of the erectable variety to minimize the aerodynamic heating problem. Possible devices of this nature include high-temperature parachutes, inflated drag devices such as balloons, kites, and inflatable lifting surfaces. The first need here is to determine the ability of various erectable devices to exert aerodynamic forces under conditions of reentry. These forces must be then related to the benefits gained by reentry trajectory control. Finally, the required temperature tolerance and strength must be compared with the design capability.

The required studies are comprehensive, embracing such varied disciplines as those in aerodynamic research to determine the effects of different reentry angles and velocities on time history of heating and deceleration and those in materials research to support the development of high-temperature, fabriclike materials for some of the control devices. The relative merits of the hot structures approach and the protected structures approach to the heating problem must also be evaluated. The structural configurations problems of reentry vehicles are very similar to those previously listed under aircraft configurations but involve more severe environmental conditions. The research recommended can be summarized as:

(1) Determine by generalized analysis the "trade-offs" between trajectory control, structural configurations, and thermal protection systems for various types of reentry vehicles, ranging through ballistic and slightly lifting to high L/D types with both high and low surface loadings.

(2) Experimental and analytical studies of erectable-fabric structures for reentry vehicles.

The Landing Problem

In the landing phase, the problem of cancelling the kinetic energy of relative motion may be accomplished either by (a) active or propulsive methods, or (b) passive or dissipative methods. In either case, the systems may be airborne or ground-installed. Retrorockets may be cited as an example of an active system; dissipative systems, which are in the majority, include conventional gear, skids, spikes, and inflatable bags.

Most needed for intelligent design of landing systems is a generalized study of families of devices. Such a study should show, for each system investigated, the maximum theoretical capability of the system, the fraction of this theoretical capability of the system that can be attained with current state-of-the-art, and the sensitivity of this capability to various design requirements.

The efficiency with which kinetic energy can be dissipated by the various systems might be measured, as in the case of reentry, against the performance of retrorockets as a yardstick, and comparisons might be drawn on the basis of weight, volume, reliability, and cost.

It appears desirable to conduct a general study of this type before spending a large amount of money developing particular devices. For state-of-the-art capability of particular devices, such a generalized study could draw upon a wealth of data already accumulated (for example, the work of refs. 19 and 20).

Extension of these studies on a proper theoretical basis may show parametric relations that may afford significant savings in experimental programs through the use of models instead of full-scale vehicles for test purposes.

Acquisition of new experimental facilities should be justified by a definitive statement of required characteristics not attainable in currently available facilities, of which there are a number. While specific problem areas related to the landing problem can be better defined upon the completion of the recommended generalized study, the following problems are of sufficient urgency to merit consideration at this time:

(1) The investigation of improved means for the landing of aircraft, including impact resistance for VTOL/STOL types, possibly utilizing ground effects.

(2) Determination of the energy-dissipation capabilities of such landing devices as inflated gas bags, crushable honeycomb, pneumatic cylinders with and without dynamic buckling of the walls, and to allow initial screening of various methods for preliminary design purposes.

(3) The determination of fundamental parametric relations governing the performance of landing systems and the scaling laws which would apply for the design of large hardware and small models.

(4) Study of recovery systems applicable to large launching vehicles, including such effects as produced during recovery at sea.

APPENDIX E

ANALYTICAL METHODS AND DESIGN ALLOWABLES

Previous sections have been concerned with the clarification of problems confronting the structural designer during conception and gestation of the design. The present section is concerned with the strength analysis of the product and the prediction of its structural capabilities.

Through the years much effort has been devoted to the problems of analytical structural mechanics and the great body of knowledge accumulated in the literature provides satisfactory solutions to many structural design problems. While refinements and improvements are both possible and desirable in many areas, there are others in which present methods for analysis and design are inadequate, serving only as a guide by which test articles may be built for verification or study. Testing in general is becoming more complex and expensive, and in some situations may be wholly impractical. Accordingly some of the more urgent problems requiring improved analytical tools are described in the following paragraphs.

Thin Shells

Thin shells will continue to be an increasingly important component of structural design in future aircraft and in spacecraft. Many space vehicles will utilize thin shell structures, not solely for cabins but for many forms of auxiliary structure as well. Despite the large amount of research effort that has gone into the study of the behavior of thin shells for the aircraft industry, there are still many unexplored regions. For example, the entire regime of radius-to-wall thickness ratios of 1,000 and more, appropriate to the vehicles now being considered, has only recently begun to be explored.

Thin shell structure may be subjected to shear, bending moment, and axial compressive loads. In addition concentrated or line loads may be imposed at the attachments to adjacent structural components. Present theories for evaluating the effects of concentrated or line loads on axisymmetrical bodies are not proven for thin shells. The ability of such structures to support concentrated load by large deformations merits investigation. The structures may or may not be pressurized in all of these conditions. Methods, either theoretical or empirical, must be developed to predict properly the behavior of such shells. These techniques must be adequate to take into account the effects of internal and external pressure interacting with applied shear and bending moment.

In rocket vehicles, wall thicknesses of tanks and body structure have steadily decreased as improvements in the tensile properties of materials have been translated into structural design. The point has been reached at which for many booster designs - as for solid-propellant motor cases used in upper-stage devices - the critical criterion is not tension but compressive loading. Under these circumstances, further improvements in tensile properties of tank materials would be useless unless increased resistance to local distortions can be provided. In the design of components which have a possible failure mode of buckling instability, there is a need for expanding the local cross section to increase the local bending stiffness. Honeycomb-sandwich or waffle-type structures are possible ways of achieving this increase. Many questions about such an approach remain unanswered, however. Little work has been done on multiwall pressure vessels. The effective transfer of load from one wall to the other to provide predicted burst strengths presents problems. Thermal gradients may cause severe stresses. Joint problems will be aggravated. An investigation is needed to determine the merits of various configurational approaches to the wall stabilization problem. The possible stabilizing effect of propellant grain (as in the motor case of a solid-propellant engine) especially for dynamic effects, requires clarification.

Thin shell design is now applied to many shapes of surface, and the applications are extending. Consideration must be given to circular and elliptic cylinders, conical surfaces, spherical and ellipsoidal surfaces, ogives, intersections of such surfaces, and double curvatures.

The following research programs are therefore indicated:

(1) Analytical methods for thin shell structure require extension into various single and combined load regimes, for all shapes, and particularly for large R/t ratios.

(2) Analytical methods must be developed for treating the introduction of concentrated loads and local deformations into thin wall shells, with and without internal pressure, based on large deflection theory.

(3) The stability of solid rocket cases receiving partial support from propellant grain under loads of short duration should be investigated.

(4) Methods should be established for treating the effects of thermal gradients and thermal strains in rocket cases and in propellant tanks.

Pressure Vessels

Many vehicles will utilize or be comprised of pressure vessels to contain an atmosphere for occupants, or a gas at low pressure as for erection or inflation, or a fluid at high pressure for the propulsion system. The state of knowledge of the strength and failure characteristics of pressure vessels (even within the earth's atmosphere) is inadequate, and research on this problem should be extended.

Except for recent advances made in rocket vehicle construction,
current design concepts for pressure vessels date back a half century L
or so. Before the missile, operating stresses were limited to a frac- 1
tion of actual base metal yield strength. Liberal factors of safety 2
were necessary to compensate for inaccuracies and ignorance. Moreover, 2
in the past most pressure vessels were constructed of ductile alloy 4
steels with thick walls.

As the strengths of materials have increased, ductility has steadily declined. In addition, the ratio of yield to ultimate stress has also increased. It now appears that the ratio of ultimate to yield stress will be approximately 1.1 for steels in the 300,000 psi class, which are contemplated for pressure vessel application. At these levels any stress raisers can be catastrophic.

Working with such materials poses additional problems. Primarily, the uniaxial tensile test is inadequate for evaluating and predicting the behavior under biaxial stress conditions. Vessels fabricated from materials that exhibit essentially the same uniaxial properties may exhibit failures totally unrelated to these properties. The influence of combined stresses on the fracture strength accordingly needs to be studied sufficiently to permit correlation of bursting strengths with known properties of many nonductile materials and for both cylindrical and spherical configurations.

Since the criteria for failure (developed tensile stress, shear stress, strain energy per unit volume, tensile strain, etc.) all vary with both materials and loading conditions, the establishment of a suitable criterion for high strength, low ductility biaxially stressed engineering materials is needed. This criterion must be capable of taking into account such additional factors as a realistic distribution of stresses and strains within the vessel wall. Further surface effects of the space environment may add still another factor into the determination of the strength of pressure vessels, and this too must be taken into account.

Numerous methods of predicting behavior of low ductility materials under biaxial stresses have been suggested. Categorically, none are entirely satisfactory. This problem is a fertile field for investigation.

The solution of many of the problems of using materials of low ductility lies perhaps in a better understanding of solid-state physics as related to the various factors which influence failure mechanisms.

Detail configuration.- Since every tank must have openings for pipes, nozzles, etc., an important area for investigation is the determination of the proper configurations for bulkhead-cylinder attachments, manhole covers, nozzle attachments, sheet laps, indeed for the reinforcement in general of discontinuities in thin shells. Joining and sealing of thick sections pose fabrication problems; placement of domes, outlets, and engine attachments involves difficult operations. A study of all of these detail problems is warranted. Evaluations of the structural efficiencies that can be expected would be useful in design.

Overall configuration.- The relative merit of various overall configurations for pressure vessels needs to be determined. What is the relative merit of a number of spheres compared to a few cylinders when the practical aspects of construction, fittings, etc., are considered? Can the joint problem be solved adequately so that the merit of intersecting spheres can be capitalized upon? Is some unusual configuration useful? A review of possible shapes, supplemented as required by detailed studies, would provide some useful answers to these questions.

The configurational problems related to pressure vessel design are evidently concerned both with detailed aspects of joints, bulkheads, etc., and with the general shape both of wall cross sections and of the body as a whole.

Crack propagation.- Much work has been done toward the development of pressurized cabins for aircraft. The type of structure used in missiles and spacecraft, however, is not in general similar to aircraft practice; the stress level may also be much higher, and the stress distribution may be quite different. Vacuum effects may also influence crack propagation in certain materials.

The entire problem of crack propagation needs reevaluation in the light of the materials, construction methods, stress distributions, and environments experienced in missiles and spacecraft operations. Certain fundamental work to evaluate the influence of cracks in the macro- and microscopic regime is especially needed. Particularly in materials with low ductility, it appears that under biaxial stresses a microscopic crack can be inordinately important. Evaluation of the effects of microscopic flaws, as well as development of reliable methods of detection would be a significant advancement.

Fail-safe design.- The pressure vessel is an excellent example of the problem of the application of "fail-safe" concepts. What is the probability of total, or catastrophic, failure for a fail-safe design?

Does anyone really know enough about fail-safe design methods to employ them skillfully? These questions seem to increase in cogency for space vehicles. Indeed the attractiveness of the "fail-safe" philosophy increases with the distance from the earth's surface, but little has yet been done to obtain a true evaluation of this significant design concept. In the case of spacecraft, meteoroid impacts underline the need for fail-safe structures. These impacts should not cause an explosive failure or result in leakage. The basic principles for neither of these requirements have been adequately spelled out. It appears that here the greatest contribution can come from the determination of the important parameters and criteria to apply for fail-safe design.

L
1
2
2
4

Research recommendations.- In summary, the following research work is required on pressure vessels:

(1) A fresh study of pressure vessel theory is indicated, starting from fundamentals, with particular reference to thin-wall membrane-like structure fabricated of high yield-ratio low-elongation material.

(2) Basic research is needed into the fundamental mechanism of failure of low-ductility materials under multiaxial stress, with particular regard for the influence of surface characteristics as they may be affected by space environment.

(3) An adequate test method is needed to determine the suitability of fabricated and processed material for use in pressure vessel construction, and to serve in establishing allowable design values.

(4) A study is required of the detail design problems which occur in thin-wall pressure vessels, leading to an evaluation of structural penalties and optimum detail configurations.

(5) A systematic investigation should be conducted of the effect of overall shape and configuration on the structural efficiency of tanks and pressure vessels under various loads and conditions.

(6) Studies should be made of multiwall pressure vessels, investigating stress distribution and detail design problems.

(7) Crack propagation effects should be reevaluated in structures and under conditions representative of spacecraft applications.

(8) The philosophy of fail-safe design should be examined, and design recommendations spelling out criteria and parametric relations should be developed.

Fatigue

Some of the problems of fatigue have been discussed in other sections of this report, and a comprehensive review of fatigue is made in reference 15. In this section it is appropriate to identify the general areas in fatigue in which gaps exist in data on allowable design properties, or in methods of applying available data to the design of flight structures.

For aircraft, continued exploration of analytical and experimental procedures for estimating fatigue life is essential. These explorations need to be supplemented by the acquisition of additional fatigue test data for materials under various environmental conditions, including high and low temperatures, vacuum, etc. Also the effects of prior temperature and load history on the residual life of structures and materials need to be determined.

For launching vehicles and spacecraft, the major problems in the present category are low-cycle fatigue, acoustically excited fatigue, and fatigue under conditions of combined stresses. Preparatory to and during its useful life, a missile or booster tank will be subjected to at least several cycles of pressurization. In the case of a liquid system tactical missile, this number may approach as many as 1,000 cycles. While the space vehicle may undergo only a few cycles, depending upon the delays and holds encountered during launch, thermal stress cycling may occur in flight because of solar radiation, heating, etc., and in all conditions, the stresses involved will probably be very close to the yield strength of the material. Most fatigue data available today are at much lower stress levels than those which will be encountered in the life cycles of missiles and spacecraft.

Acoustic energy loading is an important type of fatigue problem, and analytical methods and techniques are required to make proper allowance for it in design. A better knowledge of structural damping and response and possible alleviation systems could be used to advantage.

Fatigue data for multiaxial tensile stresses are almost nonexistent. In such circumstances methods are needed which will correlate uniaxial, biaxial, and triaxial stresses (including various stress ratios), and extensive tests should be undertaken to obtain actual design information. The side influences of the very low temperatures experienced in the containment of liquid hydrogen and helium, the effects of corrosive fluids (i.e., fluorine) and of a hard vacuum environment should also be evaluated.

The fatigue problem for spacecraft is somewhat different from that for aircraft, in that regular inspection procedures can no longer be used to take the place of uncertainty in design. There will be no opportunity to observe the incidence and growth of fatigue cracks and to modify and replace structure before such cracks become dangerous; for spacecraft, the designer must be able to meet the problem on the drawing board.

While fatigue problems are not new, fatigue has become an area of major engineering significance in aircraft, missile, and spacecraft design because the reliability and successful performance of vehicles has been jeopardized in many cases by fatigue failure. While fatigue research is being conducted by many research agencies, no satisfactory solution to the fatigue problem is available or even in prospect. Although the outlook is dismal, it is essential that increased emphasis and the best available talents be focused on the problem if flight vehicle progress is to continue at the desired rate. The following work is therefore indicated.

(1) Determination of the basic mechanism of fatigue of materials. This area of fundamental research provides a potential for a dramatic breakthrough and subsequent minimization of the fatigue problem.

(2) The continued accumulation of data on fatigue properties of structural materials under new environmental extremes, such as high and low temperatures, high vacuum, and other space conditions.

(3) Determination of the general effects of prior load and temperature history on fatigue properties to provide guidance for specific testing required with particular designs.

(4) Continued exploration of analytical and experimental methods for estimating fatigue life, with special emphasis on low-cycle fatigue and fatigue under combined stress conditions.

Design Optimization

The term "optimum design" has been somewhat misused in recent years, with the result that a kind of stigma has become attached to it. In some circles an "optimum design" is one that has been made so marginal in reliability that it is inevitably a failure. The definition of "optimum" which is intended here on the contrary, is a true, best design, such that all pertinent factors are appropriately weighed and allowed to influence the design so that the function intended is most satisfactorily carried out. On the basis of this definition there are several important problem areas deserving study in the field of optimum design.

The crux of the problem of optimum design is the proper comparison of various approaches for comparable design conditions. While for aircraft this often means the determination of the design of least weight for the design load (with the "load" broadly defined to incorporate the important design considerations), there are usually so many secondary conditions to be satisfied so that no real distinction can be drawn between an "optimum" and an "adequate compromise." What is needed is a study of fundamental factors controlling aircraft and reentry vehicle structural design with a view towards the establishment of design philosophy to serve as a framework for selecting critical design conditions. On the basis of an adequately established philosophy of design, generalized optimization studies may properly be performed of structures including fatigue, fail-safe, thermal, and aeroelastic effects as well as static strength and system reliability.

For spacecraft the design considerations involve so many new parameters that the establishment of a proper philosophy of optimum design will require an appreciable effort. Here even the basic principles of optimum design are yet to be spelled out, and they must be so spelled out if a rational procedure is to be achieved.

For space vehicles, for example, aerodynamic considerations no longer dictate the shape, and a large part of the optimization problem may lie in the choice of configuration. Furthermore the importance of optimization is magnified for spacecraft because of the increased "growth factor" for these vehicles, variously estimated at from 10 times to 1,000 times that for high-performance aircraft.

Contributions needed in this area can be classed under three headings:

(1) The establishment of the underlying principles for optimum design for space requirements: determination of the governing parameters or structural indices and methods of comparing true merits of different designs.

(2) The invention of new configurations suggested by the established analytical procedures.

(3) Demonstration of the validity of the indicated solutions.

Structural Design Criteria

Structural design criteria are established by consideration of the interaction of two factors: (1) environment including applied loads, and (2) ability of the structure to withstand the environment and the loads. The environment itself is covered in the early portion of this report as an important area for research emphasis. It is expected that research here would eventually lead to probability tables and curves for varying magnitudes of environmental loading, such as gust loads, number of impacts and size of meteoroid particles per unit area per unit of time or distance, or radiation intensities, for example.

In designating the problem of rational design criteria as a deserving area for research, it is to be emphasized that methods for evaluating the second factor, the performance of the structure, are in dire need of attention. For example, the 1.5 factor between design load and ultimate strength used for most components in manned aircraft in the past has sufficed to take care of quality variations in materials of construction, analytical inadequacies, fabrication tolerances, unexpected overloading, service wear and damage, and in some cases fatigue, impact, and combinations of adverse environmental conditions. Reliability standards for such vehicles, however, are so high that the function of the factor of safety has been, according to common interpretation, to preclude failure in an absolute sense, rather than to establish a certain probability of success. Nevertheless all the elements entering into the equation are probabilistic in nature. Recent trends toward effectively lower factors of safety are justified by better methods of analysis and quality control, but such advances are unquestionably offset in an efficient design of minimum redundancy which uses relatively untried materials of brittle nature in a poorly defined environment. No framework exists by which these various factors can be assessed in quantitative fashion.

L
1
2
2
4

A small change in the factor of safety can mean a significant change in structural weight. In the face of strong pressures to reduce these factors of safety, it becomes necessary to examine the more fundamental issues: namely, what degree of reliability is actually desired, and how can it be translated into a rational design criterion.

The problems in this area are:

(1) To devise methods of assessing the performance of the structure in quantitative terms which will permit the establishment of rational design criteria. Such methods must take cognizance of the probabilistic nature of failure phenomena and the factors which influence them.

(2) To devise practical procedures whereby the knowledge which exists regarding environment, loads, and structural performance may be brought together to determine reliability; or alternatively, whereby design requirements may be identified for a stipulated reliability.

APPENDIX F

MATERIALS SELECTION AND DEVELOPMENT

Throughout the problem areas delineated in the preceding sections, the importance of the interaction between structural design and material characteristics and response has been evident. The constant emphasis on the significance of materials development in structural design suggests that it is desirable for structures and materials engineers to work closely together to produce improved materials having the properties most needed for structural design. It is hard to demonstrate that until recently there has been any substantial cooperation between materials developers and structural designers. There are two outstanding examples of this lack of cooperation: (1) because the structural designer has not communicated the importance of low material density to the material developer, no real effort has been made to develop low density structural materials; (2) because it admirably serves his purposes, the developer of materials has so concentrated on the "modulus of rupture" test that the structures man has not been able to use materials of potential merit because meaningful mechanical property data have not been available. Increased cooperation between materials developers and structural users should be immensely profitable in obtaining improved structural materials.

To begin with, the structural designer must define clearly the desirable material properties for the various flight applications. Some of these desirable properties will be discussed in the following sections.

Sustained Supersonic Flight

The long periods of kinetic heating encountered in sustained supersonic flight require different material approaches to be used, for example, than those for the short-time heating of ballistic missiles. Lightweight solutions to the thermal structures problems will have to be achieved, however, before the low-altitude supersonic vehicle is feasible. Here structural and material limits govern flight performance capabilities. Because of these limits the recent achievements in propulsive devices and in aerodynamic drag control which have provided practically unlimited speed potentials can not be utilized. The temperatures generated aerodynamically in the structure and from the propulsion medium reduce material strength, and increase deformation and life problems. Higher propulsive capabilities are associated with higher noise levels, and these have introduced the relatively new fatigue problem of structural response to acoustical noise. Such problems present a challenge requiring the best combined efforts of both the structures and materials investigators. Specific problem areas are:

(1) To evaluate and improve the structural utilization of refractory metals, nonmetallics, and ceramic composites including coatings to prevent oxidation, for sustained high-temperature exposure.

(2) To investigate materials and joining problems for use in the construction of high-temperature radomes and windshields and to determine the importance of atmospheric dust in the design of such structures.

(3) To investigate further the potential of beryllium as a structural material and to improve its effectiveness in such applications, including its use in composite materials.

(4) To develop advanced heat-protection materials for long exposure such as coated pyrolytic graphite for leading edges and controls, and foamed ceramics for high-temperature insulation.

(5) To investigate methods for the structural utilization of new materials such as composites of whiskers, flakes, and advanced fibers.

(6) To investigate ways of increasing the internal damping of materials and study the applicability of such internally damped materials to the acoustic fatigue problem.

(7) To investigate the fundamental mechanism of fatigue of materials with a view to the development of fatigue-resistant materials.

Reentry

Materials developed for ballistic missile nose cones have contributed to the solution of the short-time, high-acceleration type of reentry. For more gradual reentry, as for man-carrying vehicles, further developments are needed. For example, there is the specific problem area concerned with the development of "wide-band" thermal protection systems to provide maximum tolerance for guidance and control errors upon the initiation of reentry. The requirements are for systems to operate efficiently both for long times at low heating rates and for short times at high heating rates. In addition there may be a need for constant external (aerodynamic) contours. The interesting approaches to these requirements include specially designed composite materials utilizing high-strength filaments or whiskers of refractory ceramics, foamed ceramics, or perhaps employing an improved form of graphite. Not to be neglected are advanced low-density, low-conductivity ablating systems such as those designed to produce a char layer of pyrographite in situ during ablation. Here again the combination of structures and materials talents is required to insure the mechanical integrity of material and char layer, even as these disciplines must be combined to examine thermomechanical interactions in all heat-protection systems.

The specific developments needed are:

(1) Materials suitable for "wide-band" thermal protection systems, combining the characteristics of high effective heat capacity, low thermal conductivity, and adequate mechanical integrity.

Pressure Vessels and Cryogenic Tanks

Material development problems for pressure vessels divide into two categories: (1) metals, and (2) nonmetallics or composites. The metals have the inherent ability to carry the biaxial stresses characteristic of pressure vessel application. In so doing they may be more prone to such design complications as brittle fracture, but still show advantage over the filamentary materials, which are capable of carrying load only in the direction of the filaments. The large effort under way to increase the capabilities of the steel and titanium alloys for pressure vessel applications deserves continued support.

On the other hand, boosters and tanks fabricated from nonmetallic materials appear to offer many advantages. High strength-weight ratios are attainable with glass-filament-wound, plastic-reinforced vessels, and clearly the ultimate in glass filament technology has not been reached. For example, the use of flattened fibers or flakes makes possible the achievement of improved biaxial properties. A principal drawback to production of reliable vessels of such materials is means of attachment of bulkheads, nozzles, filler bosses, carry-through structures, and the like. While similar problems exist in metallic vessels, solutions in nonmetallics are of particular difficulty.

Perhaps even more important for many applications than the high strength-weight ratios of the filament wound plastic vessels is their low density. The trend toward lower chamber pressures, for example, tends to make the absolute value of wall thickness of importance. Here, as in the vast majority of aerospace structural applications, the most important material property is the density.

Inspection methods for the nonmetallic materials must be improved. Primarily nondestructive methods on the whole are inadequate. Detection of defects and nondestructive evaluations of bonds are at best crude and unreliable. Improvements in these techniques would advance the reliability and probably increase the usage of nonmetallics for all applications.

A new class of problems is introduced in the design of tanks for cryogenic temperatures. These problems range from those of brittle fracture at the low temperatures to the provision of extremely low thermal conductivities for the materials adjacent to the tanks so that the low temperatures may be economically maintained. While there is a considerable backlog of experience in the laboratory with cryogenics, the extension of this experience to the construction of flight vehicles may require substantial cooperation among the several technologies involved, particularly between those of structural design and materials development.

Areas for research effort are summarized as follows:

(1) The development of filamental, flake, and bonded-foil composite materials.

(2) The development of methods of introducing attachments and discontinuities into constructions of filamental materials.

(3) The development of methods of inspection for nonmetallic materials.

(4) The development of structural and insulation materials for cryogenic tanks.

Low-Density Material Applications

If a systematic study is made of the relation between material properties and flight structural design, the one property which is universally important is the density. Characteristics like strength or stiffness may be equally important for specific applications; more often they contribute less directly to the design weight than the material density does.

For advanced flight vehicles, particularly those which utilize flimsy, erectable structures of large surface area, low-density materials are necessary to avoid weight penalties because of the "minimum gage" problem - the problem of a minimum thickness which it is practical to use. For meteoroid impact resistance low density may be helpful. For radiation shielding (protons and electrons) low-density (low atomic weight) materials are most effective. For compression or local bending the importance of low density has long been recognized for aircraft; it is equally valuable throughout the range of flight structures. Thus, for example, the low density (combined with the high Young's modulus) of beryllium would make it a "natural" material for space vehicles if brittleness and fabrication problems could be more fully overcome.

The following effort is indicated:

(1) Studies directed first toward the reduction of material density and secondly toward the improvement of strength-density or stiffness-density ratios.

(2) Cooperative studies in the fields of structures and materials to determine the possibilities of oriented voids in materials to reduce density with minimum loss in mechanical properties.

(3) The development of hollow reinforcing filaments and whiskers and their utilization in composites.

(4) The continued development of beryllium as a structural material.

REFERENCES

1. NACA Subcommittee on Structures: A Special Report on Recommended NASA Research for Space Structures and Related Problems. Sept. 1958.

2. Rhode, Richard V., and Houbolt, John C.: The Impact of Space Technology on Research and Development - Structures and Materials. Presented at Gen. Assembly, AGARD, Copenhagen, Oct. 1958.

3. Heldenfels, Richard R.: Space Structures. 1959.

4. Bisplinghoff, R. L.: Remarks on the Influence of Space Environment on Materials and Structures of Space Vehicles. May 21, 1959.

5. NASA Research Advisory Committee on Structural Design - Panel on Aircraft: Structural Design Research Required to Support the Development of Future Aircraft. Oct. 1959 (unpublished).

6. NASA Research Advisory Committee on Structural Design - Panel on Spacecraft: Recommended Areas of Research on Structures for Space Vehicles. Oct. 1959 (unpublished).

7. NASA Research Advisory Committee on Structural Design - Panel on Boosters and Tanks: Recommended Research on Boosters and Tanks. Oct. 1959 (unpublished).

8. NASA Research Advisory Committee on Structural Design - Panel on Re-entry and Landing: Problems of Re-entry and Landing With Implications for Research on Structures and Materials. Oct. 1959 (unpublished).

9. Steinberg, Morris, Fox, J., and Augenstein, Bruno: A Proposed Ground and Flight Program to Develop Space Age Materials. American Rocket Society Paper No. 1103-60, presented at the Structural Design of Space Vehicles Conference, Santa Barbara, April 6-8, 1960.

10. Anon.: Report on Composite Structural Materials. National Academy of Sciences, Materials Advisory Board, Nat. Res. Council, Rep. No. MAB-146-M, Dec. 18, 1958.

11. Anon.: Report on Thermal Protection Systems. National Academy of Sciences, Materials Advisory Board, Nat. Res. Council, Rep. No. MAB-151-M, June 1, 1959.

L
1
2
2
4

12. Anon.: Materials Problems Associated With the Thermal Control of Space Vehicles. National Academy of Sciences, National Research Council, Materials Advisory Board, Rep. No. MAB-155-M, Oct. 20, 1959.

13. Lad, Robert A.: A Survey of the Materials Problems Resulting From the Low Pressure and Radiation Environment in Space. NASA TN (Proposed), 1960.

14. Steurer, W. H.: Material Problems in Space Technology. Rep. No. ZS-MT-004, Convair-San Diego, Mar. 19, 1959.

15. Anon.: An Integrated Fatigue Research Program. NASA Inter-Committee Fatigue Panel. Mar. 21, 1960.

16. Gazley, C., Jr., Kellogg, W. W., and Vestine, E. H.: Space Vehicle Environment. Jour. Aero/Space Sci., vol. 26, no. 12, Dec. 1959, p. 770.

17. Bjork, R. L., and Gazley, C., Jr.: Estimated Damage to Space Vehicles by Meteoroids, USAF Project RAND Res. Memo Rm 2332, Feb. 20, 1959.

18. Heldenfels, Richard R.: Frontiers of Flight Structures Design. Presented at the Durand Centennial Conference on Aeronautics and Astronautics, Stanford Univ., Aug. 1959.

19. Ali, Ahmin, and Benson, Leonard R.: Cushioning for Air Drop, Pt. IX. Bibliography of Literature Pertaining to the Absorption of Impact Energy. Univ. Texas, Austin, Texas, June 9, 1957.

20. Karnes, Charles H., Turnbow, James W., Ripperger, E. A., and Thompson, J. Neils: High Velocity Impact Cushioning. Pt. V. Energy-Absorption Characteristics of Paper Honeycomb. Univ. Texas, Austin, Texas, May 25, 1959.